

# SMWDs as SGRs/AXPs and the lepton number violation

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**Abstract.** Possible nature of strongly magnetized white dwarfs (SMWDs) is studied. It is shown that for relatively low values of the equatorial surface magnetic field  $B \sim 10^9 - 10^{11}$  G they can be good candidates for soft gamma-ray repeaters and anomalous X-ray pulsars (SGRs/AXPs). For the case of iron SMWDs the influence of a neutrinoless electron to positron conversion on the SGRs/AXPs luminosity is estimated.

**Keywords:** double charge exchange; degenerate Fermi gas; stellar magnetic fields; white dwarfs; soft gamma-ray repeaters; anomalous X-ray pulsars; lepton number violation

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## INTRODUCTION

It has recently been shown that SMWDs can be progenitors of the superluminous supernovae Ia [1, 2, 3]. In parallel, we have applied in Refs. [4, 5] the concept of the SMWDs, developed in Ref. [1], to the study of the reaction of the double charge exchange

$$e^- + X(A, Z) \rightarrow X(A, Z - 2) + e^+, \quad (1)$$

which can happen only if the neutrinos are of the Majorana type, implying thus the lepton number violating process of electron capture by a nucleus  $X(A, Z)$ , which was in our case  ${}^{56}_{26}\text{Fe}$ .

In Table 4 [5], we presented the ratio of the calculated change in the luminosity  $\Delta L$  of the SMIWDs to the solar luminosity  $L_\odot$ , employing the necessary input from Table 2 [5],  $|\langle m_\nu \rangle| = 0.4$  eV and 0.8 eV, and the nuclear radius  $R = 1.2 A^{1/3} \approx 4.59$  fm. For convenience, we present the results for  $\Delta L$  below, labeled by the corresponding absolute value of the effective mass of Majorana neutrinos  $|\langle m_\nu \rangle|$ .

- For the Fermi energy  $E_F = 20 m_e$ ,

$$(\Delta L)_{0.4} = 6.07 \times 10^{18} \text{erg s}^{-1}, \quad (\Delta L)_{0.8} = 2.42 \times 10^{19} \text{erg s}^{-1}. \quad (2)$$

- For the Fermi energy  $E_F = 46 m_e$ ,

$$(\Delta L)_{0.4} = 7.64 \times 10^{21} \text{erg s}^{-1}, \quad (\Delta L)_{0.8} = 3.04 \times 10^{22} \text{erg s}^{-1}. \quad (3)$$

Here,  $m_e$  is the electron mass.

## SMIWDs AS SGRs/AXPS

During the last decade the observational astrophysics has made substantial progress in the study of the SGRs/AXPs sources. The McGill Magnetar Catalog [6] contains 26 such objects called magnetars. Generally, it is believed that SGRs/AXPs are the neutron stars (NSs), powered by the decay of strong surface magnetic fields of the order

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<sup>†</sup> deceased

up to  $10^{15}$  G [7, 8]. They are specified by a long rotational period  $P \sim (2 - 12)$  s and by its time derivative  $\dot{P} \sim (10^{-11} - 10^{-15}) \text{ ss}^{-1}$ , larger than for ordinary pulsars with  $\dot{P} \sim 10^{-15} \text{ ss}^{-1}$ .

Let us note that in the pulsar model, the observed X-ray luminosity  $L_X$  is supposed to come from the loss of the rotational energy of the NS

$$\dot{E}_{\text{rot}}^{\text{NS}} = -4\pi^2 I \frac{\dot{P}}{P^3}, \quad (4)$$

where  $I$  is the momentum of inertia of the NS. Besides, the surface dipolar magnetic field strength at the equator,  $B_e$ , and the characteristic age of the pulsar,  $\tau$ , are

$$B_e = \left( \frac{3c^3 I P \dot{P}}{8\pi^2 R^6} \right)^{1/2} \equiv \frac{m}{R^3}, \quad \tau = \frac{P}{2\dot{P}}, \quad (5)$$

where  $R$  is the radius of the star at the equator,  $c$  is the velocity of light and  $m$  is the magnetic moment of the rotating magnetized star.

In the last years, SGRs/AXPs sources were observed [6, 9, 10, 11, 12, 13, 14] which, if considered as rotation-powered NSs, provides  $\dot{E}_{\text{rot}}^{\text{NS}} < L_X$  and  $B_e \sim (10^{12} - 10^{13}) \text{ G} < B_c = m_e^2 c^3 / (e\hbar) = 4.414 \times 10^{13} \text{ G}$ . This is in discord with the magnetar model that requires inverted inequalities. There are alternative hypotheses about the nature of SGRs/AXPs possessing magnetic field lower than the critical field  $B_c$ . E.g., it was shown in Refs. [15, 16, 17] that these low magnetic field magnetars can be alternatively described as massive rapidly rotating magnetized WDs.

Analogously, we have proposed in [5] that such magnetars can be considered to be the SMIWDs. For this study, we have chosen two SGRs/AXPs, namely SGR 0418+579 and Swift J1822.6-1606, for which the rotational period  $P$  and the spin-down rate  $\dot{P}$  are well known [6, 9, 10, 11, 12]. Our calculations have shown that the loss of the rotational energy of the rapidly rotating SWIMDs can also describe the observed luminosity of these compact objects.

Here, we report on an improvement of these calculations and include the results for the new low magnetic field compact object 3XMM J185246.6+003317 [13, 14].

For the pulsar model, the values of the mass and radius of the NS are set to  $M = 1.4 M_\odot$  and  $R = 10 \text{ km}$ , whereas for the WD model, the choice of these parameters is  $M = 1.4 M_\odot$  and  $R = 3000 \text{ km}$ , in accord with Refs. [15, 17, 16]. In the approach of the SMIWDs, we take  $M = 2 M_\odot$  and the radii from our Table 3 [5].

Next we analyze the data for the above mentioned compact objects.

- SGR 0418+5729 (data from <sup>a)</sup> Ref. [9], <sup>b)</sup> Ref. [10])

$$\begin{aligned} P(s) &= 9.0784^a), & \dot{P}(ss^{-1}) &= 4 \times 10^{-15}^a), \\ d &= 2 \text{ kpc}^a), & \Delta L_X &= 7.5 \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}^b). \end{aligned} \quad (6)$$

From  $\Delta L_X$  and the distance  $d$  one obtains for the luminosity and the age

$$L_X = 3.6 \times 10^{30} \text{ erg s}^{-1}, \quad \tau = 36 \text{ Myr}. \quad (7)$$

As described above, one gets from these numbers the results:

$$B_{\text{NS}} = 6.4 \times 10^{12} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{NS}}| = 7.5 \times 10^{28} \text{ erg s}^{-1}, \quad (8)$$

$$B_{\text{WD}} = 7.1 \times 10^7 \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{WD}}| = 6.7 \times 10^{33} \text{ erg s}^{-1}, \quad (9)$$

$$R_{\text{SMIWD}} = 423 \text{ km}, \quad B_{\text{SMIWD}} = 4.3 \times 10^9 \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| = 1.91 \times 10^{32} \text{ erg s}^{-1}, \quad (10)$$

$$R_{\text{SMIWD}} = 186 \text{ km}, \quad B_{\text{SMIWD}} = 2.2 \times 10^{10} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| = 3.7 \times 10^{31} \text{ erg s}^{-1}. \quad (11)$$

Comparing the results for the spin-down luminosity, presented in Eqs. (8) - (11), with the luminosity  $L_X$  of Eq. (7), one can see that the loss of the rotational energy of the SMIWDs as well as the loss of this energy of the WD can explain  $L_X$ , but for the NS,  $|\dot{E}_{\text{rot}}^{\text{NS}}| < L_X$ .

Let us note that according to Table 1 [9], in the time interval from July 2009 to August 2012 the luminosity of this star diminished by 1150 times! If in the last 3 years the reduction in the luminosity were the same then it would be now  $L_X = 3.0 \times 10^{27} \text{ erg s}^{-1}$ , rather than  $L_X = 3.6 \times 10^{30} \text{ erg s}^{-1}$ . In our opinion, remeasurement of its  $\Delta L_X$ ,  $P$ , and  $\dot{P}$  would be highly desirable.

- Swift J1822.6-1606 (data from Ref. [11])

$$\begin{aligned} P(s) &= 8.4377, & \dot{P} (s s^{-1}) &= 8.3 \times 10^{-14}, \\ d &= 5 \text{ kpc}, & \Delta L_X &= 4 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}. \end{aligned} \quad (12)$$

From  $\Delta L_X$  and the distance  $d$  one obtains for the luminosity and the age

$$L_X = 1.2 \times 10^{32} \text{ erg s}^{-1}, \quad \tau = 1.61 \text{ Myr}. \quad (13)$$

However, as argued by Scholz et al. [12], Swift J1822.6-1606 could have a comparable distance to that of the Galactic region M17, which is  $1.6 \pm 0.3$  kpc. In that case,

$$L_X = 6.4 \times 10^{31} \text{ erg s}^{-1}. \quad (14)$$

For the magnetic fields and the spin-down luminosities one obtains

$$B_{\text{NS}} = 2.8 \times 10^{13} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{NS}}| = 1.9 \times 10^{30} \text{ erg s}^{-1}, \quad (15)$$

$$B_{\text{WD}} = 3.1 \times 10^8 \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{WD}}| = 1.7 \times 10^{35} \text{ erg s}^{-1}, \quad (16)$$

$$R_{\text{SMIWD}} = 423 \text{ km}, \quad B_{\text{SMIWD}} = 1.9 \times 10^{10} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| = 5.0 \times 10^{33} \text{ erg s}^{-1}, \quad (17)$$

$$R_{\text{SMIWD}} = 186 \text{ km}, \quad B_{\text{SMIWD}} = 9.8 \times 10^9 \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| = 9.6 \times 10^{32} \text{ erg s}^{-1}. \quad (18)$$

Comparing the results for the spin-down luminosity, presented in Eqs. (15) - (18), with the luminosity  $L_X$  of Eq. (14) one can see that the loss of the rotational energy of the SMIWDs as well as the loss of this energy of the WD can explain  $L_X$ , but for the NS,  $|\dot{E}_{\text{rot}}^{\text{NS}}| < L_X$ .

- 3XMM J185246.6+003317

This low magnetic field magnetar was discovered first by Zhou et al. (2014 - [13]). Its phase-coherent timing analysis was later redone by Rea et al. (2014 - [14]). The results of both works are similar. We restrict ourselves with the data from Ref. [14]:

$$\begin{aligned} P(s) &= 11.5587, & \dot{P} (s s^{-1}) &< 1.4 \times 10^{-13}, \\ d &= 7.1 \text{ kpc}, & \Delta L_X &< 6.64 \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}. \end{aligned} \quad (19)$$

Let us note that the distance  $d = 7.1$  kpc in [14] was adopted from [13]. From  $\Delta L_X$  and the distance  $d$  of Eq. (19) one obtains for the luminosity and the age

$$L_X < 4.0 \times 10^{33} \text{ erg s}^{-1}, \quad \tau > 1.31 \text{ Myr}. \quad (20)$$

However, as argued by Rea et al. [14], suggested distance of 7.1 kpc for 3XMM J185246.6+003317 from the similarity of its foreground absorption and the near supernova remnant Kesteven 79 can be misleading, since the supernova remnant is much younger. Then for

$$d = 5 \text{ kpc} \quad L_X < 2.0 \times 10^{33} \text{ erg s}^{-1}, \quad (21)$$

and for

$$d = 2 \text{ kpc} \quad L_X < 3.2 \times 10^{32} \text{ erg s}^{-1}. \quad (22)$$

For the magnetic field and the spin-down luminosity one obtains

$$B_{\text{NS}} < 4.3 \times 10^{13} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{NS}}| < 1.3 \times 10^{30} \text{ erg s}^{-1}, \quad (23)$$

$$B_{\text{WD}} < 4.8 \times 10^8 \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{WD}}| < 1.1 \times 10^{35} \text{ erg s}^{-1}, \quad (24)$$

$$R_{\text{SMIWD}} = 423 \text{ km}, \quad B_{\text{SMIWD}} < 2.9 \times 10^{10} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| < 3.2 \times 10^{33} \text{ erg s}^{-1}, \quad (25)$$

$$R_{\text{SMIWD}} = 186 \text{ km}, \quad B_{\text{SMIWD}} < 1.5 \times 10^{11} \text{ G}, \quad |\dot{E}_{\text{rot}}^{\text{SMIWD}}| < 6.3 \times 10^{32} \text{ erg s}^{-1}. \quad (26)$$

Comparing the results for the spin-down luminosity with the  $L_X$  one can see that the loss of the rotational energy of the SMIWDs can explain  $L_X$  for  $R_{\text{SMIWD}} = 423$  km and  $d \leq 5$  kpc and for  $R_{\text{SMIWD}} = 186$  km and  $d \leq 2$  kpc, whereas the WD model can explain  $L_X$  also for  $d = 7.1$  kpc. On the contrary, the loss of the rotational energy of the NS is by about two orders of the magnitude smaller.

As for a possible role of the double charge exchange reaction (1), comparison of the obtained spin-down luminosities with  $(\Delta L)_{0.4}$  and  $(\Delta L)_{0.8}$  of Eqs. (2) and (3), respectively, shows that the energy produced by this reaction cannot influence sizeably the luminosity of the compact objects, considered above as rapidly rotating SMIWDs.

## DISCUSSION OF THE RESULTS AND CONCLUSIONS

We explored the SMIWDs as rapidly rotating stars that can be considered as GSRs/AXPs. We have shown that using the observational data for the compact objects SGR 0418+579, Swift J1822.6-1606 and 3XMM J185246.6+003317, the loss of the spin-down luminosity calculated in the simple SWIMD model can reproduce the observed X-ray luminosities. However, the energy produced by the reaction of the double charge exchange (1) cannot influence sizeably the luminosities of the compact objects considered as rapidly rotating SMIWDs. It means that the study of the reaction (1) in the SMIWDs, using simple model [1] with the ground Landau level and at the present level of accuracy of measurements of the luminosity and energy of the cosmic gamma-rays cannot provide conclusive information on the Majorana nature of the neutrino, if the absolute value of its effective mass is  $|\langle m_\nu \rangle| \leq 0.8$  eV.

On the other hand, more realistic models of SMWDs [2, 3, 18] already exist that can be used to improve the estimate of the yield of the reaction (1). Besides, new observational facilities are expected to provide soon the data also for fainter compact objects, in which the effect of this reaction could be observed. Let us mentioned one of them, the satellite Gaia (in operation from 2013), whose results will have tremendous influence on many topics in the WD research [19].

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